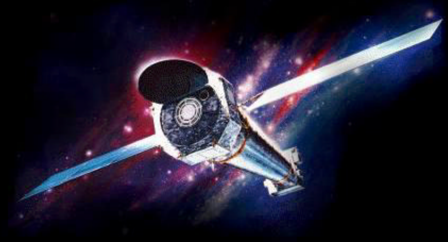

# Managing radiation degradation of CCDs on the Chandra X-ray Observatory

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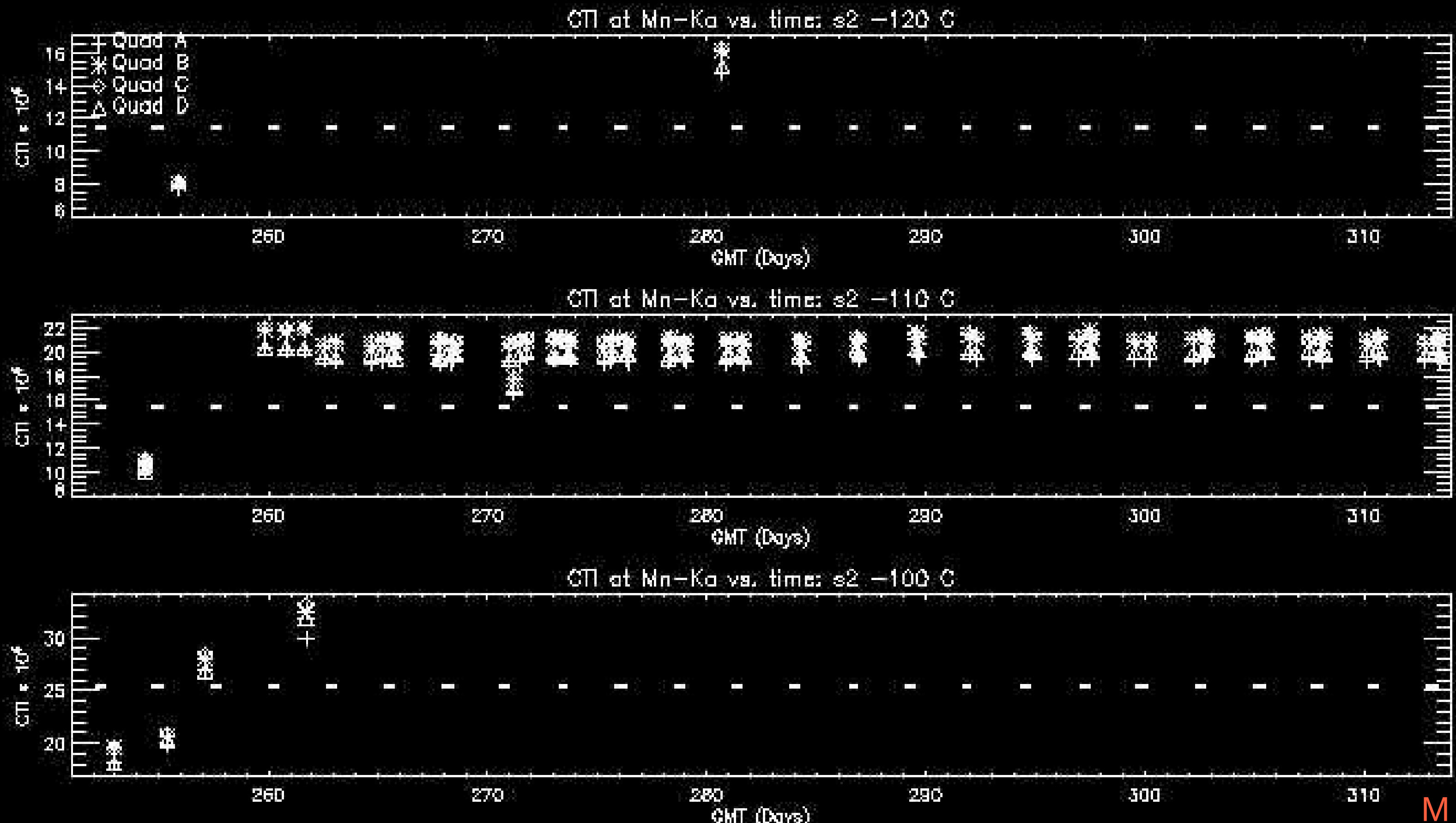
# FI-CCD CTI degradation

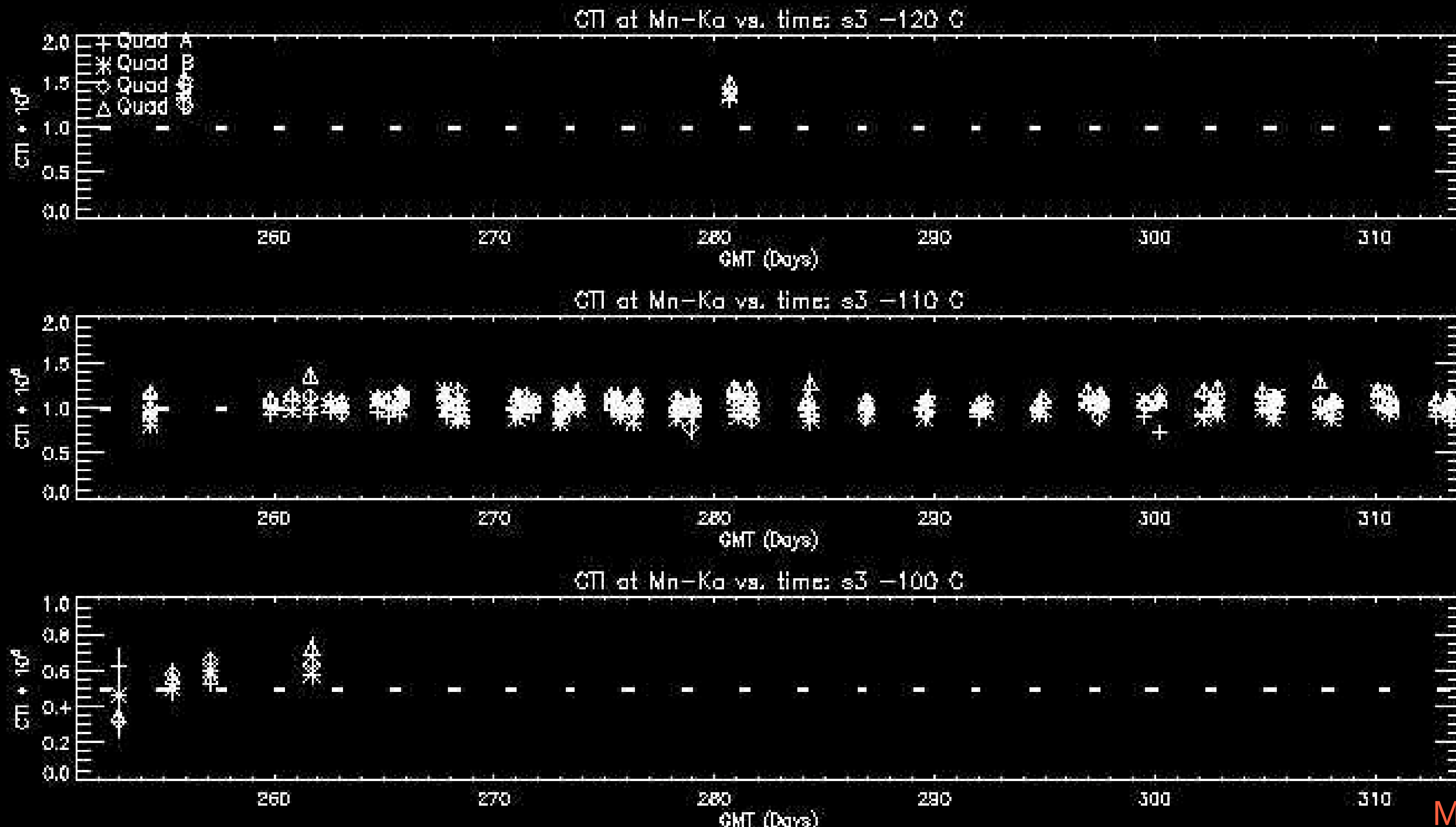
- Charge transfer inefficiency (CTI) of front-illuminated (FI) CCDs
  - Rapid increase in CTI ($4\times10^{-5}$/orbit @ -100 °C) after first light




MIT ACIS

# BI-CCD CTI stability

- Charge transfer inefficiency (CTI) of back-illuminated (BI) CCDs
  - Relatively stable CTI ($<0.1\times10^{-5}$/orbit @ -100 °C)




MIT ACIS

# ACIS CTI anomaly

- On-orbit evidence for damage by soft (0.1–0.5 MeV) protons
  - ACIS had been in focal plane during 8 radiation-belt passages.
    - Focal plane is well shielded against penetrating radiation.
      - Line-of-sight shielding analysis missed scattering from mirrors.
    - No degradation occurred with ACIS in NIL position during perigee.
    - Inserted gratings substantially reduced CTI degradation.
  - CCD degradation mode suggested soft protons.
    - Increase in CTI of back-illuminated CCDs remained small.
      - BI CCDs have 45-µm-thick Si shielding charge-transfer channel.
    - Dark current of all CCDs remained small.
    - Constant serial CTI showed that frame-store area is shielded.
  - Cal measurements before first light found no CTI degradation.
- SRIM transport to focal plane is consistent with AP8 environment.
- On-ground proton irradiation of CCDs reproduced in-flight results.

# Radiation protection

- The *Chandra X-ray Observatory* is in a high elliptical orbit.
  - 140-Mm-altitude (23-$R_\oplus$ geocentric) apogee, 2.65-d period
  - 10-Mm-altitude (3-$R_\oplus$ geocentric) perigee $\Rightarrow$ radiation belt
  - Only real-time communication during DSN contacts
    - Nominally 3 DSN contacts/d for data dumps and commanding
    - Normally executes 1-week observing plan
- Revised operating procedures to protect ACIS against radiation.
  - Radiation-protection configuration
    - Translate ACIS into NIL position; power down video boards.
    - Close door of HRC (in focal position); ramp down high voltage.
    - Retract LETG or HETG from optical path, for most belt passages.
  - Radiation protection during all belt passages
  - Radiation protection strategies for space weather
    - Autonomous, commanded, and scheduled protection

# Management strategies

- Scheduled protection
  - Move ACIS to NIL position for all radiation-belt passes.
    - Estimate inner-magnetosphere environment from AP8.
      - Pad predicted boundary against inaccuracies and variations.
- Commanded intervention
  - Monitor estimated soft-proton environment in *Chandra*’s orbit.
    - Developed model for entire *Chandra* soft-proton environment.
    - Use real-time space-environment data to drive model.
  - When needed, halt load and command ACIS to NIL position
    - Typically wait for DSN contact, but can arrange special comm.
- Autonomous protection
  - *Chandra* radiation monitor (EPHIN) measures hard-proton flux.
  - Upon trigger, OBC halts load and moves ACIS to NIL position.
    - Avoids rapid CTI degradation from rad-belt-config error or SEP.

# EPHIN radiation monitor

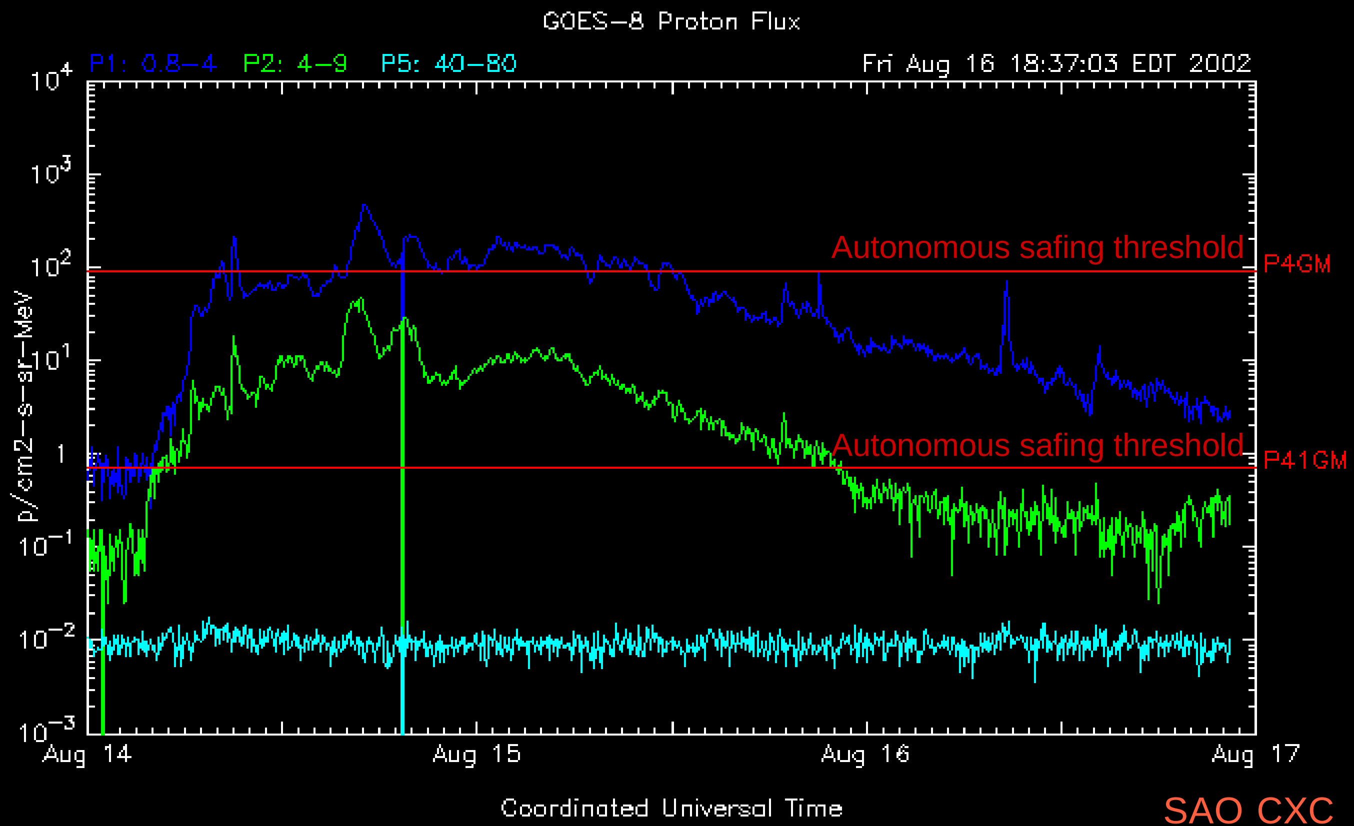
- Description of *Chandra* radiation monitor
  - Electron, Proton, Helium Instrument (EPHIN)
    - 4 electron channels (0.25–10.4 MeV) plus integral (> 8.7 MeV)
    - 4 proton channels (4.3–53 MeV) plus integral (> 53 MeV)
    - 4 helium channels (4.3–53 MeV/n) plus integral (> 53 MeV/n)
  - SOlar & Heliosphere Observatory (SOHO) flight spare
    - University of Kiel COSTEP (LION+EPHIN) experiment
- Use for *Chandra*
  - Record all EPHIN channels for download during DSN contacts.
  - Monitor 3 channels for triggering autonomous protection.
    - Defense against rapid damage to instruments
      - Large solar proton events (SPE)
      - Radiation-belt entry without proper protection of instruments
    - P4 (4.3–7.8 MeV), P41 (41–53 MeV), and E1300 (2.6–6.2 MeV)

# Real-time environment

- *Chandra* radiation-monitor real-time data during DSN contacts
  - Nominally 3 1-h DSN contacts/d
  - Not sensitive to lower-energy (< 4 MeV) protons
- NOAA Space Environment Center (SEC) provides real-time data
  - Space-environment data Updated at 1- or 5-min intervals
  - NOAA's Geostationary Operational Environmental Satellites
    - GOES X-ray, energetic proton & electron detectors; magnetometer
  - NASA's Advanced Composition Explorer (ACE)
    - In L1 orbit, 0.01-AU sunward (solar-wind upstream)
    - Relevant ACE instruments
      - Solar Isotope Spectrometer (SIS) $\Rightarrow$ hard protons
      - Electron, Proton, Alpha Monitor (EPAM) $\Rightarrow$ suprathermal ions
      - Magnetometer & Solar-Wind EPAM $\Rightarrow$ thermal plasma and field
  - MAG-SWEPAM-driven predictor of geomagnetic activity ($K_p$)

# GOES EPHIN estimator

- NOAA SEC data
  - RT hard protons
- Use for *Chandra*
  - Indicator of autonomous safing
    - GOES-P2 ⇒ EPHIN-P4
    - GOES-P5 ⇒ EPHIN-P41
  - Head start on re-planning

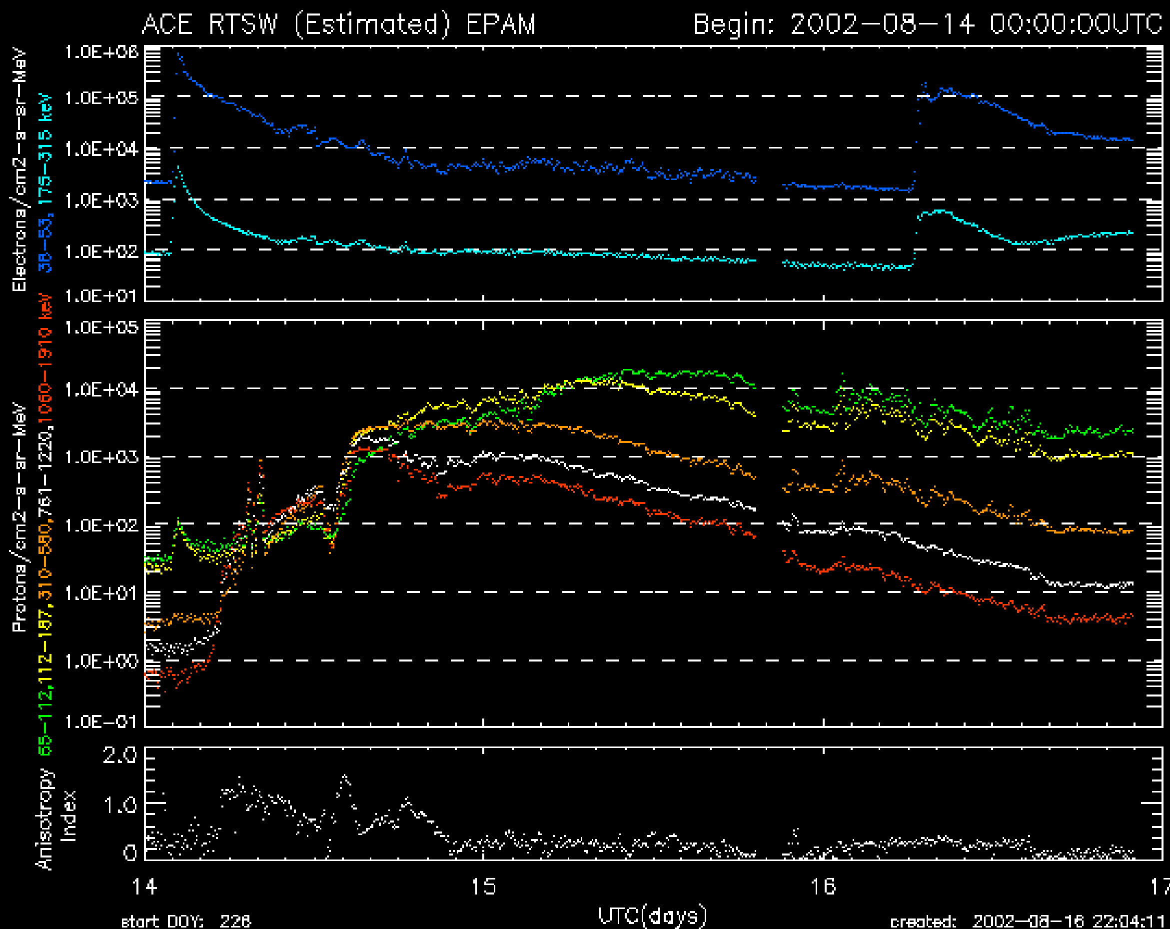



SAO CXC

Solar protons > 5 MeV typically penetrate to geosynchronous orbit (6.6 $R_\oplus$).

# ACE EPAM soft protons

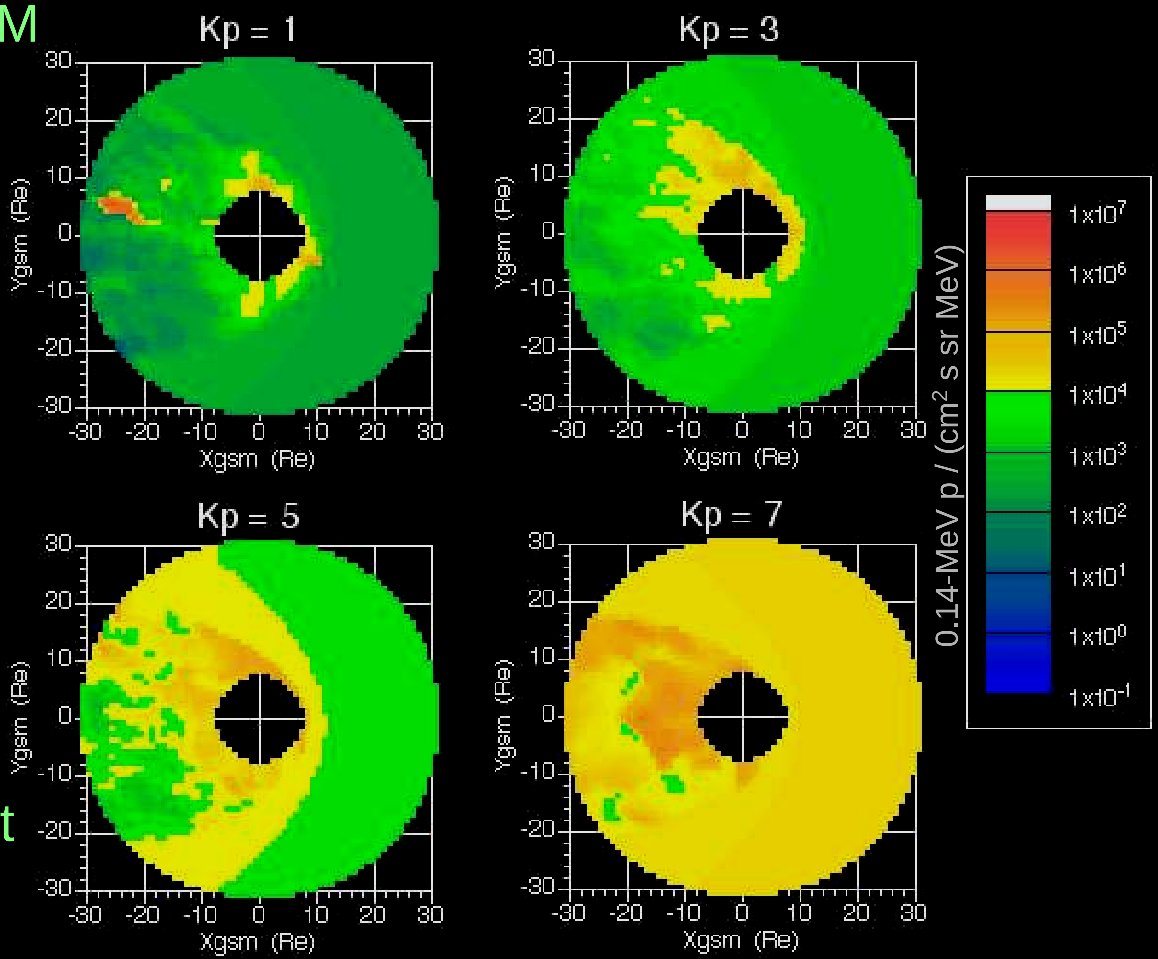
- NOAA SEC data
  - RT soft protons
  - RT soft electrons
- Use for *Chandra*
  - Real-time proton environment
    - All for solar wind
    - Partial for magnetosheath & magnetosphere
  - Damaging protons
    - EPAM-P3 channel 0.14-MeV protons
      - CXC alert if fluence high




NOAA SEC

# Chandra radiation model

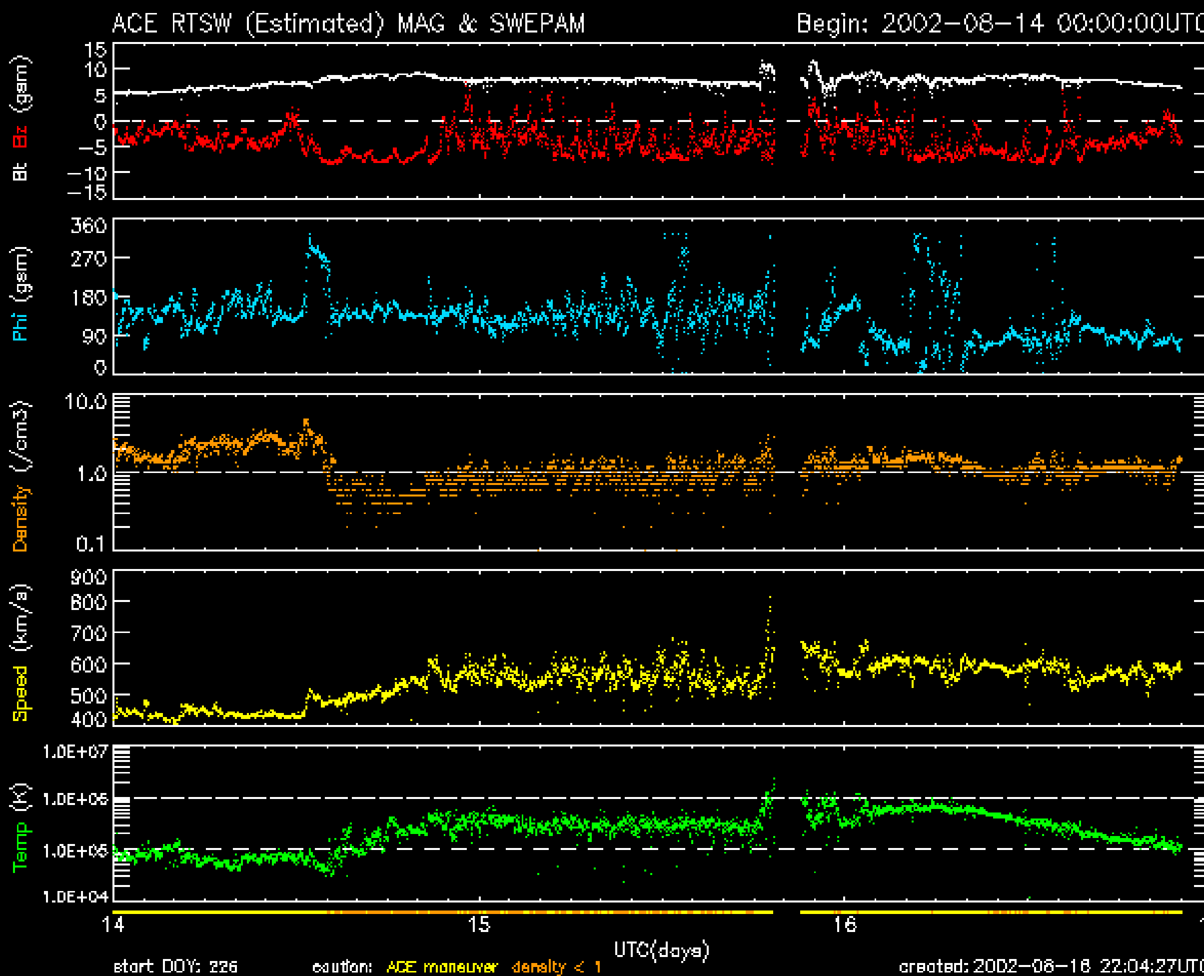
- Archival-data-based CRM
  - 0.14-MeV protons
    - *Geotail* EPIC
    - *Polar* CEPPAD
  - Streamline mapping
    - GSM coordinates
  - Correlated to $K_p$
    - Magnetosphere
    - Magnetosheath
    - Solar wind
- CRM flux
  - Calculate flux in orbit
  - Integrate to fluence
  - Project future fluence




Jacobs Sverdrup

# ACE MAG-SWEPAM

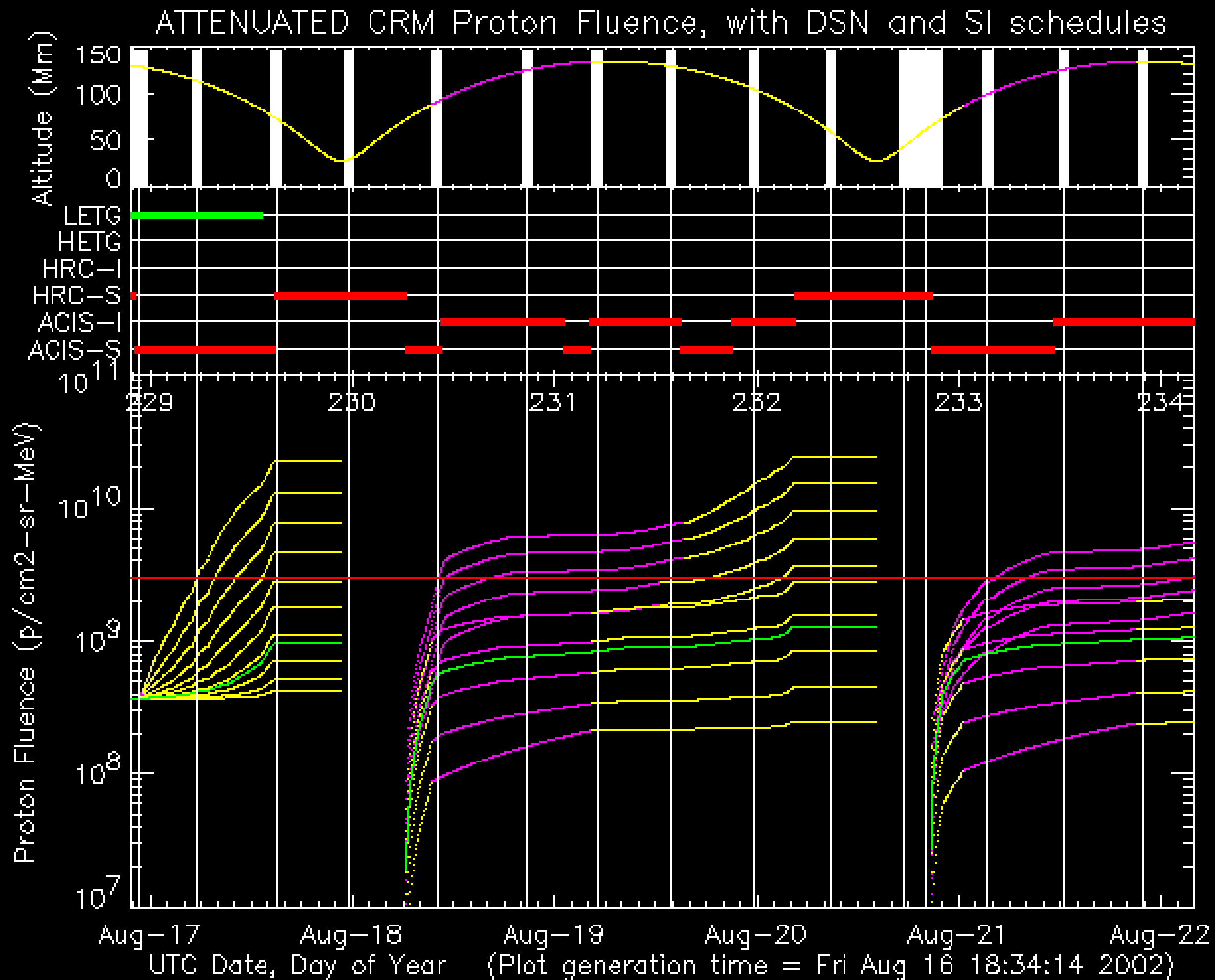
- NOAA SEC data
  - RT solar wind
    - Density & speed
    - Magnetic field
    - Temperature
  - RT Costello $K_p$
    - ACE-driven neural net
    - Geomagnetic activity
- Use for *Chandra*
  - $K_p$-driven CRM
    - RT soft proton
    - $\Delta K_p = 1 \Rightarrow$ proton flux roughly double




NOAA SEC

# Real-time CRM estimator

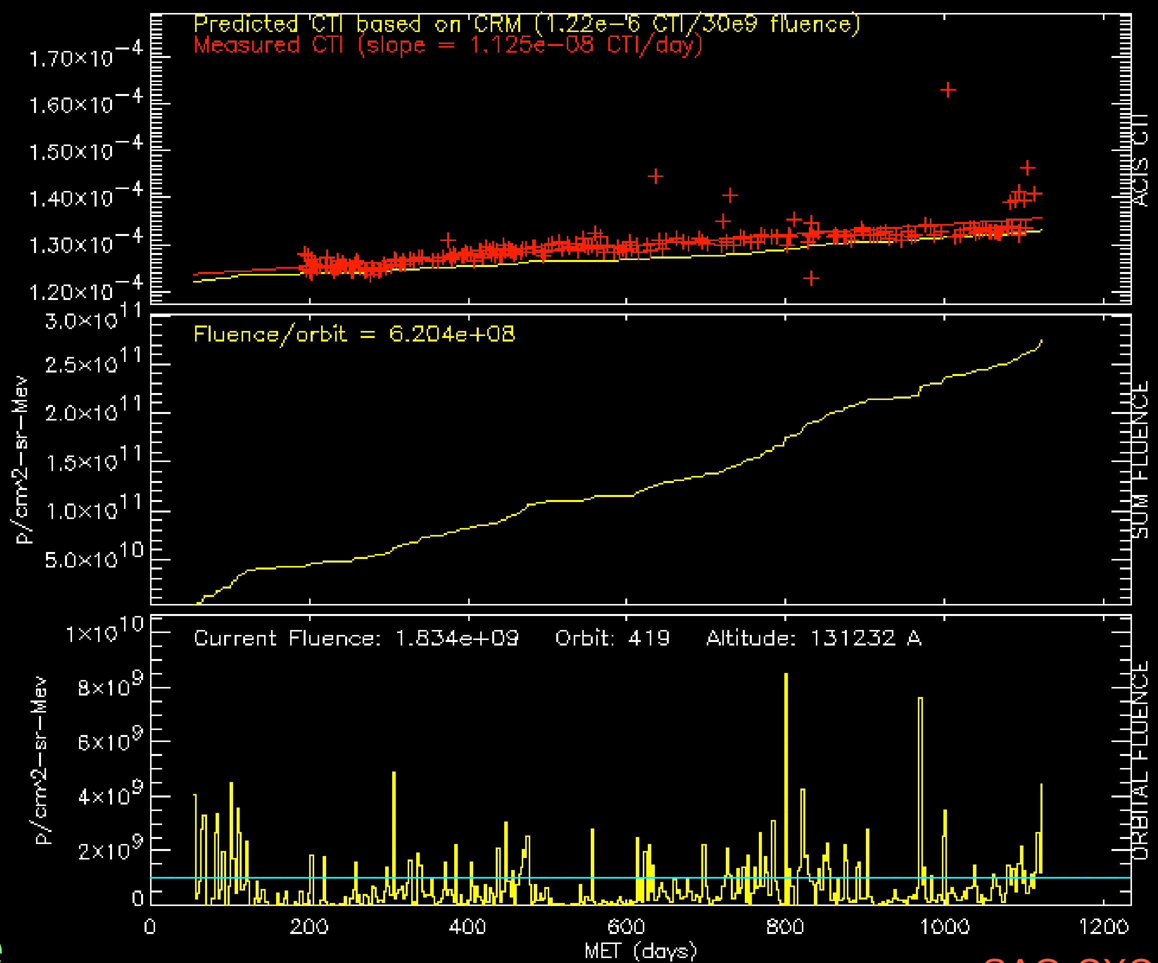
- Inputs
  - ACE EPAM P3 ⇒ solar-wind 0.14-MeV-p flux
  - ACE MAG-SWEPAM ⇒ $K_p$
    - $K_p$ + CRM ⇒ magnetospheric 0.14-MeV-p flux
  - *Chandra* config. ⇒ transmission
    - HRC: 0
    - HETG-ACIS: 0.2
    - LETG-ACIS: 0.5
    - Bare ACIS: 1




SAO CXC

# FI-CCD CTI status

- Initial degradation
  - $\Delta CTI = 12 \times 10^{-5}$
  - $3 \times 10^{12}$ 0.14-MeV p/(cm$^2$ sr MeV)
    - 8 rad-belt passes
    - AP8 environment
  - $4 \times 10^{-17}$/AP8-fluence
- Ensuing degradation
  - $dCTI/dt = 0.4 \times 10^{-5}$/y
  - $0.09 \times 10^{12}$ 0.14-MeV p/(cm$^2$ sr MeV)/y
    - Rad-belt protected
    - CRM environment
  - $5 \times 10^{-17}$/CRM-fluence




SAO CXC

# Summary

- Identified cause of ACIS CTI anomaly.
  - Soft protons scatter off x-ray mirrors into focal plane.
  - Protons reaching buried channel cause displacement damage.
- Stopped rapid degradation of ACIS front-illuminated CCDs.
  - Hide ACIS in NIL position during radiation-belt passes.
  - Lowered CCD temperature to –120 °C, reducing FI-CCD CTI.
- Implemented strategy to control degradation outside belts.
  - Employ autonomous, intervening, and scheduled protection.
    - Developed tools to estimate soft-proton flux throughout orbit.
- Radiation-degradation management preserves utility of CCDs.
  - FI-CCD CTI is fair and degradation rate is within budget.
    - Average I-array CTI = $13\times10^{-5}$, increasing at $0.39\times10^{-5}$/y.
  - BI-CCD CTI is good and degradation rate is within budget.
    - Center S-array CTI = $1.7\times10^{-5}$, increasing at $0.13\times10^{-5}$/y.